Anomalous Transport Models Applied to HSX

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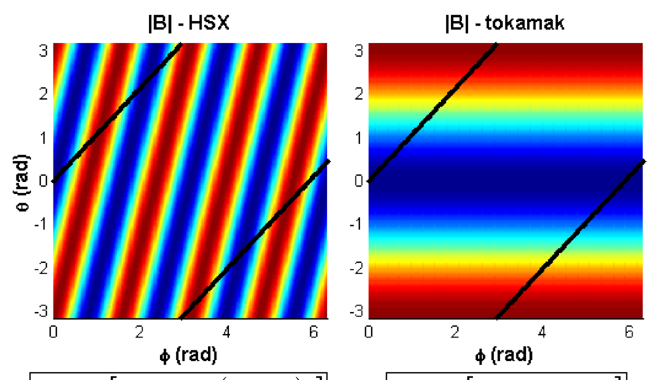
Overview

- HSX is dominated by anomalous transport, as the quasi-helical symmetry greatly reduces neoclassical transport.
  - Experimental energy and particle fluxes are much larger than neoclassical calculations.
  - Edge Langmuir probe measurements demonstrate large fluctuation levels and particle flux.
- Electron drift wave models that include trapped electron modes (TEM) provide order-of-magnitude agreement with power balance energy flux and 3D DEGAS particle flux in inner half of plasma.
- Using modeled fluctuation levels comparable to measured edge fluctuation levels, model edge transport is closer to experimental edge transport.

HSX Geometry and Model Assumptions

- HSX has a helical axis of symmetry in |B|.
- Comparison of |B| on a flux surface between HSX (N=4, m=1) and tokamak.
- Field line with $\iota \approx 1$ is superimposed.



$B = B_0[1+\varepsilon_H \cos(N-m\iota)\phi]$ $B = B_0[1+\varepsilon_T \cos(\iota\phi)]$

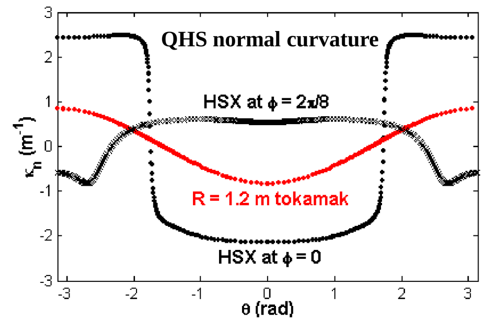
- Small effective toroidal ripple, $\varepsilon_T \approx .0023$.

⇒ Dominant particle trapping comes from helical ripple, ε_H (0.14 at r/a=1).

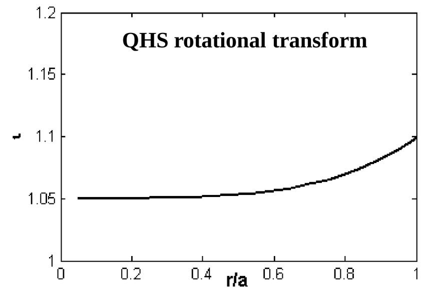
⇒ Reduced connection length, $L_c = q_{eff}R = R/|N-m\iota| \approx 1/3R$

- Field line curvature is different from tokamak.
- $\kappa_{N,max} \sim 1/45\ cm^{-1} \neq 1/R$

⇒ $\varepsilon_n = L_n/45$



- Global magnetic shear $\hat{s}$ is very small



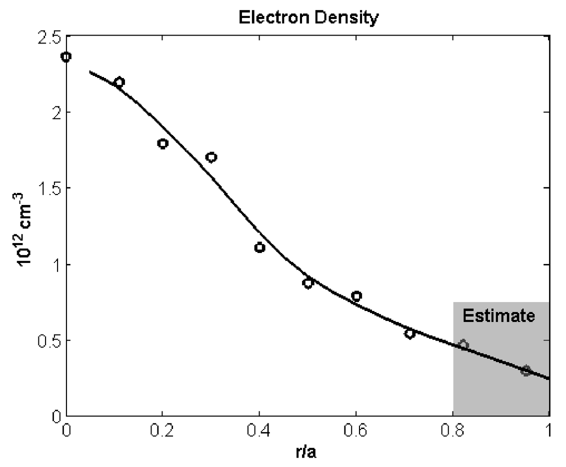
Assumptions

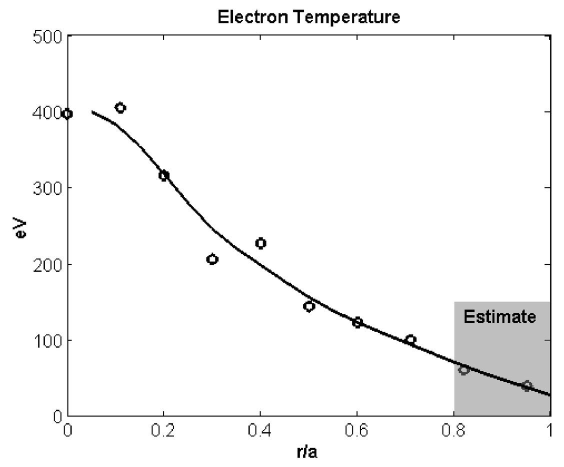
- ECRH absorbed power into electrons: $P_{abs}(r) \sim \left(1-(r/a)^2\right)^{40}$
- No radiation included.
- Loss trough ions is negligible.

⇒ "Experimental" heat flux: $q_{tot}(r) = \frac{1}{r}\int_0^r rP_{abs}(r)dr$

Model Profiles

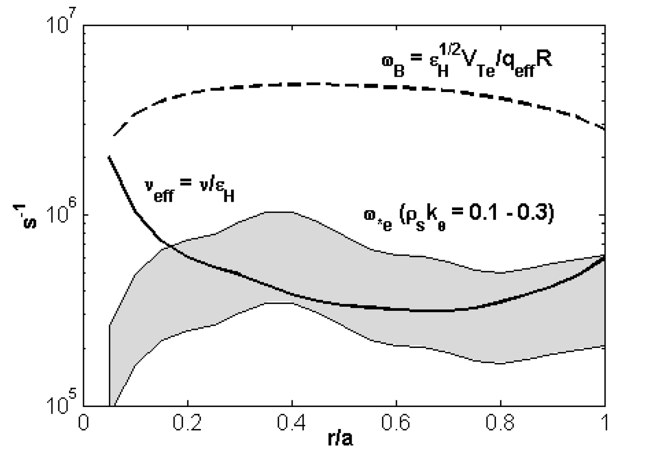
- Density and temperature profiles from Thomson scattering for central resonance heating at $\langle n_e\rangle = 1.5 \times 10^{12}\ cm^{-3}$.
- Edge parameters are estimates only.

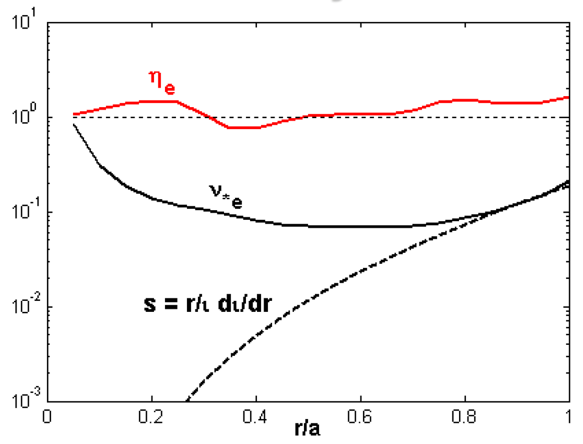




Drift Wave Transport Models Applied to HSX

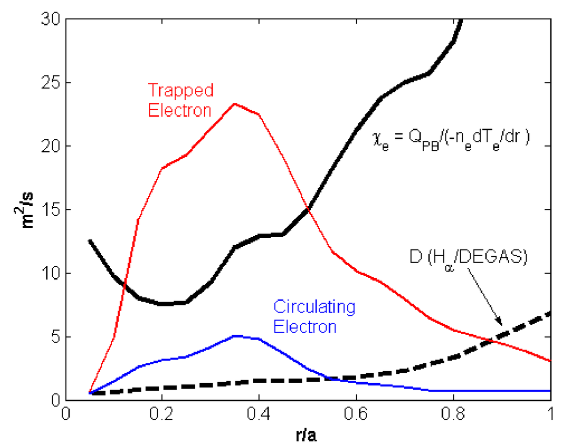
ECRH Plasmas Produce Low Collisionality Electrons





- With low collisionality ($\nu_{*e} \sim 0.1$) and helical ripple ($\varepsilon_H = 0.14$ at r/a=1), trapped electron instabilities are likely to be present.
- Very small global magnetic shear.

Theoretical Transport Coefficients – Slab Models



Trapped electron (TE) (Dominguez & Waltz, 1987)

$$\chi_e = \varepsilon^{1/2}\frac{\omega_{*e}}{k_\perp^2}\left[\frac{\omega_{*e}}{\nu_{eff}},1\right]_{min}$$

Circulating electron (CE) (Dominguez & Waltz, 1987)

$$\chi_e = \frac{\omega_{*e}}{k_\perp^2}\frac{\omega_{*e}}{\omega_{te}}\left[1,\frac{\nu_e}{\omega_{te}}\right]_{max}$$

- Trapped electron instabilities dominate circulating electron instabilities in these estimates.
- Both are order-of-magnitude agreement to experimentally inferred coefficients, but do not follow radial profile.
- Models including global magnetic shear (s or L_s) are off by many orders of magnitude.

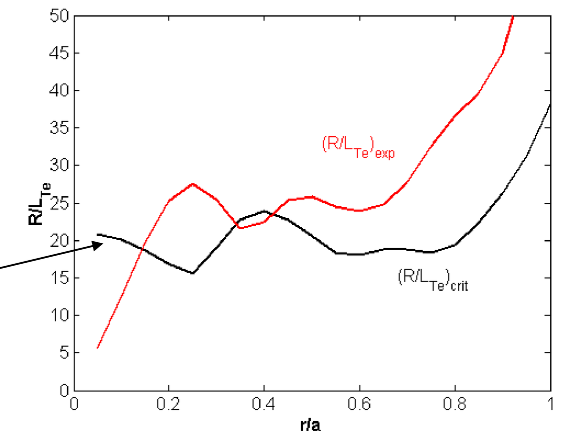
ETG Critical Gradients

Tokamak (Jenko et al., 2001)

$$(R/L_{T_e})_{crit} = \max\{(1+\tau)(1.33+1.91\hat{s}/q), 0.8R/L_n\}$$

W7-AS (Jenko & Kendl, 2002)

$$(R/L_{T_e})_{crit} = \max\{1.23(1+\tau), 0.8R/L_n\}$$



- Normalized T_e gradients are larger than critical gradients determined from linear stability ETG calculations for W7-AS, also a low shear stellarator.
- The critical gradient is determined by large $\tau = Z_{eff}T_e/T_i$ at core, $\eta_e > 0.8$ for most of plasma.

Many Edge Models Incorporate Collisional DW or Resistive MHD

- Current plasmas are collisionless even at the edge ($\nu^* < 1$, $\alpha = \frac{k_{||}^2 T_e}{m_e \nu_e \omega} >> 1$).
- Simple collisional DW growth rate and transport estimates are small.
- In the quasi-helically symmetric configuration, there is a vacuum magnetic well throughout the plasma edge.
- Transport estimates for resistive interchange modes (Shaing & Carreras, 1985; Carreras & Diamond, 1989) are orders of magnitude off from experimental estimates.

⇒ Neither collisional DW or resistive pressure gradient driven turbulence is expected to be substantial at the edge under present operating conditions.

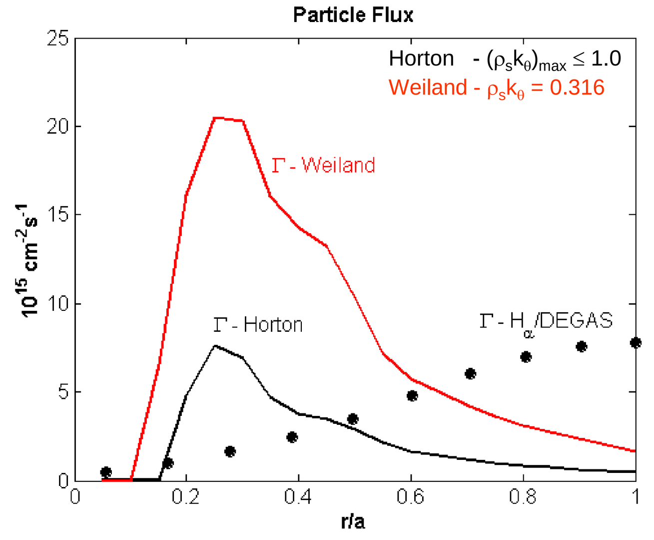
Horton Electron Drift Wave Model (1976)

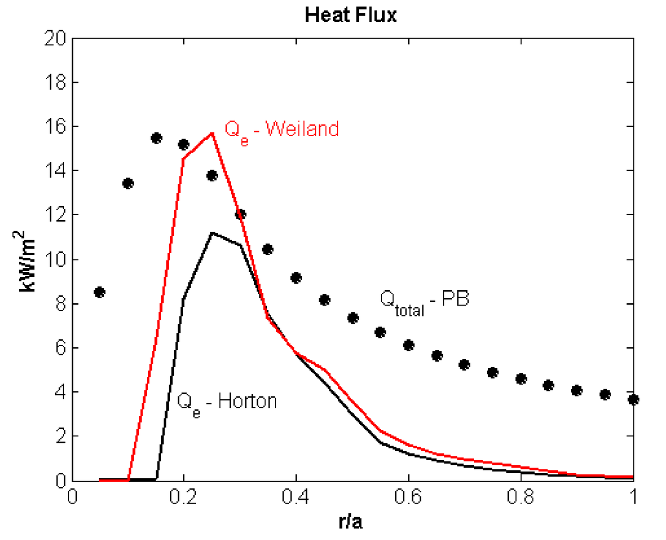
- Electron drift wave model covering all collisionality.
- Dominant instability comes from trapped electrons owing to low collisionality.
- Fluctuation estimates:
  - Horton suggests using $|e\varphi/T_e|^2 = \alpha(\rho_s/L_n)^2(L_n/L_n)$
  - Instead, use (Liu et al.) $|e\varphi/T_e|^2 \leq (5/36)(\rho_s/L_n)^2$

Weiland ITG/TEM Model

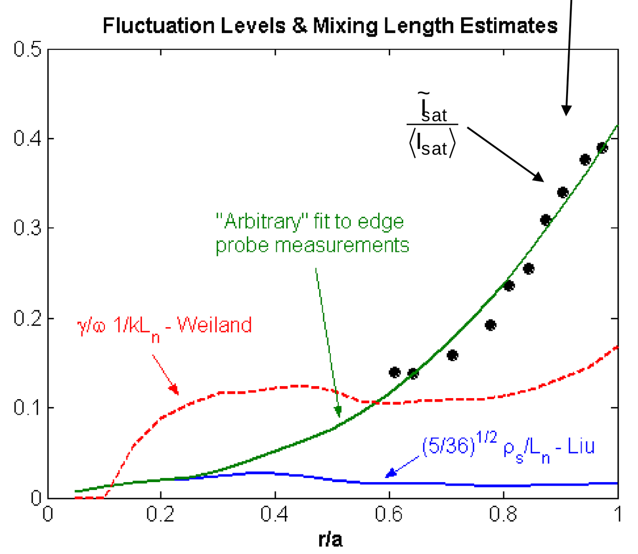
- Toroidal ITG/TEM model treating trapped electrons as a fluid.
- TEM provides instability ($T_i/T_e << 1$ and $\eta_i < 1$).
- Fluctuation estimate:

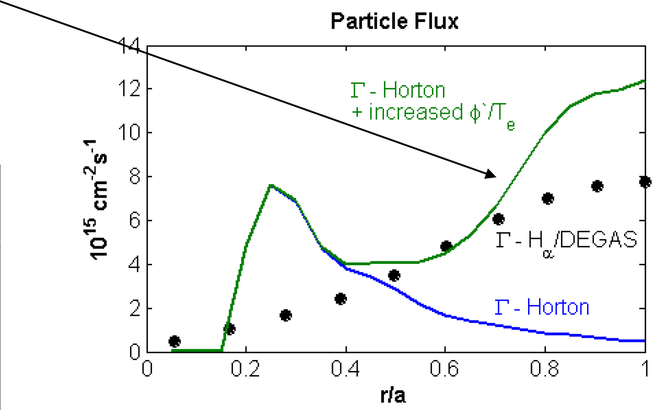
$$\frac{\tilde{\varphi}}{T_e} \approx \frac{\gamma}{\omega}\frac{1}{kL_n}$$

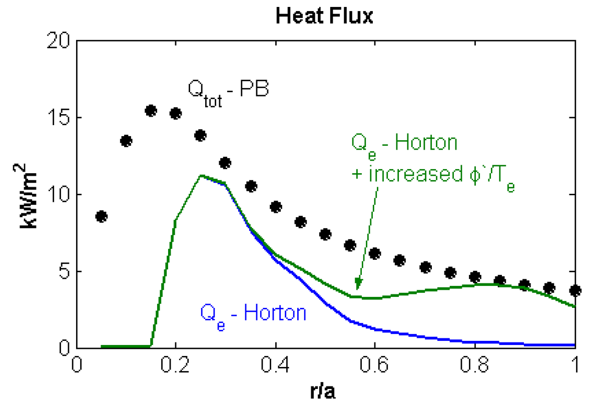




- Growth rates from both models are similar because TEM is the dominant instability.
- Both models provide order-of-magnitude agreement to experiment in inner half of plasma.
- Both models predict negligible transport towards the edge.
- Increasing the model fluctuation levels near the edge to match experimental I_{sat} fluctuation levels provides higher model edge transport.







Conclusion & Future Directions

- Under present operation conditions, electron drift wave models that include trapped electron instabilities produce order-of-magnitude agreement with experimentally inferred transport fluxes.
- Using modeled fluctuation levels comparable to measured edge fluctuation levels, the modeled edge transport is closer to experimental edge transport.

Possible Future Work (Collaborations)

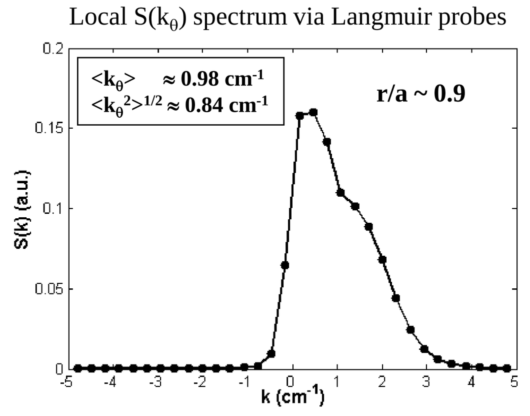
- To account for full 3D geometry, linear stability needs to be calculated numerically (e.g., ballooning mode, flux tube, or global codes) for present operational regimes ($\nu_{*e} << 1$, $T_e/T_i >> 1$, $\eta_i < 1$).
- Determine if the predicted microstability changes significantly for varied vacuum magnetic configurations through the addition of auxiliary coils, e.g. adding mirror terms or modifying the well depth.
- Determine if non-linear simulations can predict fluctuation levels large enough to match experimental fluctuation levels.

Edge Turbulence Measurements from Langmuir Probes

Fluctuation Levels

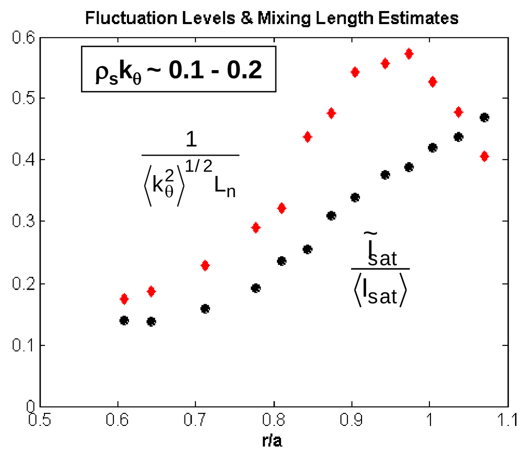
- Fluctuation levels ($\langle \tilde{I}_{sat}\rangle/\langle I_{sat}\rangle$) are as large as 40% at the separatrix.
- Mean wavenumbers measured via probes are ~ 1 cm^{-1}, with $\Delta k \sim k$.

Local $S(k_\theta)$ spectrum via Langmuir probes



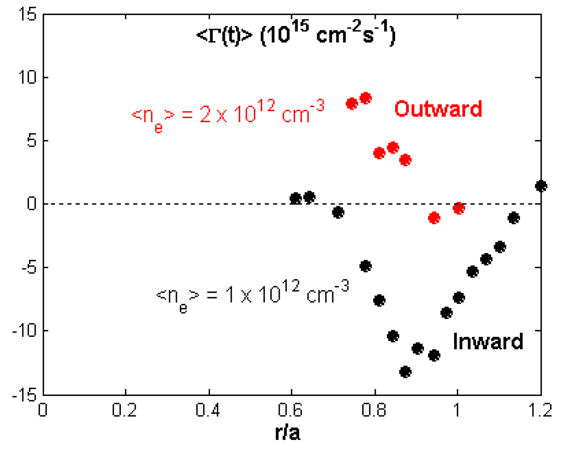
- Density gradient scale lengths estimated via mean I_{sat} and Thomson Scattering are ~ 2-5 cm towards the edge.
- Fluctuation levels correlate with simple mixing length estimates in the edge, but are smaller.

$\langle n_e\rangle = 1 \times 10^{12}\ cm^{-3}$

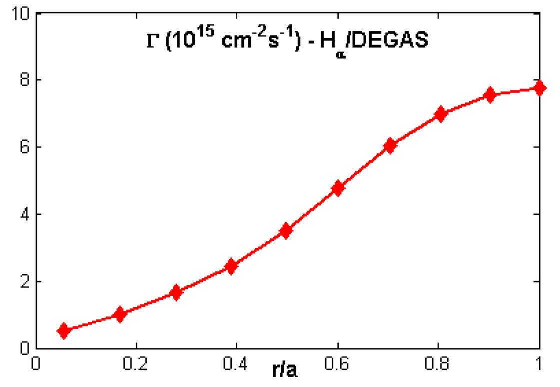


Particle Fluxes

- Magnitude of measured particle flux is comparable to H_α/3D DEGAS.
- However, the profile shape is inconsistent.
- Direction of measured transport changes with line-averaged density.

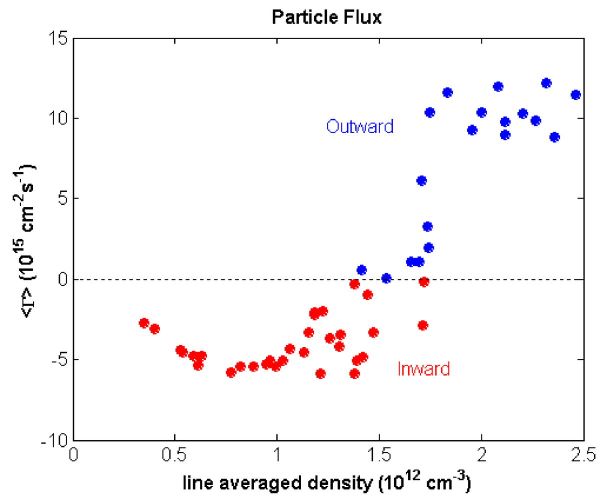


$\langle n_e\rangle = 1.5 \times 10^{12}\ cm^{-3}$

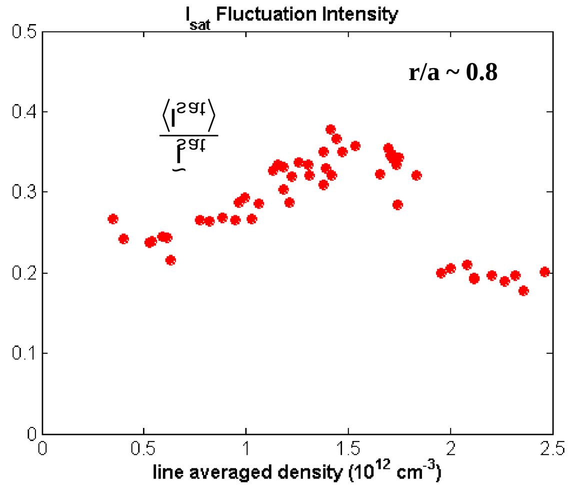


Density Dependence

- Measured transport is directed inward at $\langle n_e\rangle \leq 1.7 \times 10^{12}\ cm^{-3}$ and outward above.



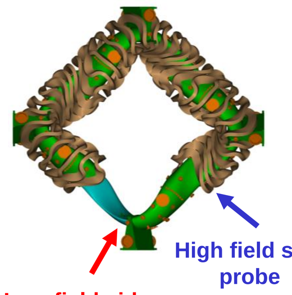
- Fluctuation intensities drop above $\langle n_e\rangle \sim 1.7\times10^{12}\ cm^{-3}$, where transport changes direction.



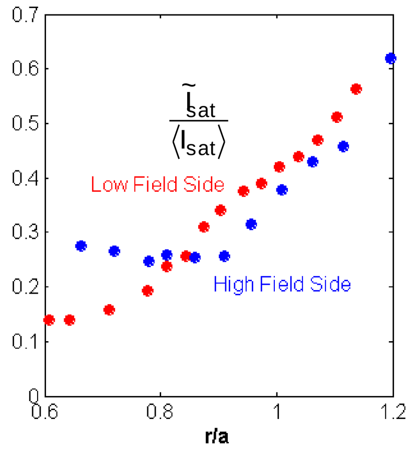
- There is a significant fraction of superthermal electrons at lower densities.
- These could affect standard Langmuir probe interpretation.
- Floating potential profiles also show significant change in edge E_r profile – potential E_r shear affects?

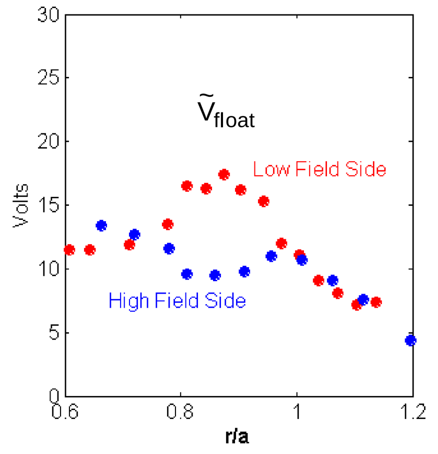
Is the Measured Particle Flux Asymmetric?

- To test if the measured particle flux is asymmetric around the machine, transport was measured at two toroidal locations.



- Mean I_{sat} and V_{float} profiles are comparable outside r/a ~ 0.8.
- There are some differences in the fluctuation levels.





- The direction of transport is similar.